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Evaluation of sheath electric field in a low-temperature hydrogen plasma by saturation spectroscopy at Balmer-α line of atomic hydrogen

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The measurement of sheath electric field is a difficult task in low-temperature plasma diagnostics. Although various methods on the basis of laser Stark spectroscopy have been developed to date, they need high-power tunable lasers and sophisticated experimental skills. A low-cost, easy-to-use method is highly demanded to understand the physics of the sheath and to optimize plasma processing technologies.

The principle of laser Stark spectroscopy is the evaluation of the electric field from the energy level structure of an atom or a molecule which is perturbed in an electric field by Stark effects. In many cases a laser-aided spectroscopic method is used for detecting the energy level structure. The difficulty of this method is caused mainly by the trade-off between the sensitivity to a weak electric field and the difficulty in the detection of energy levels perturbed by the electric field. Highly excited states (or Rydberg states) have sensitive Stark effects to a weak electric field. Therefore, many researchers have tried to employ Rydberg states as the probe for the sheath electric field measurement. However, Rydberg states are difficult to be detected since the transition probability decreases steeply with the principal quantum number. Although laser-induced fluorescence-dip spectroscopy has succeeded in detecting a Rydberg state of atomic hydrogen with a principal quantum number higher than fifty [1], it needs two pulsed tunable lasers.

In this work, we changed our approach to the detection of the Stark effects of lower-lying states. The detection of a low-energy state is rather easy since it has a large transition probability. However, since the magnitude of the energy shift of the low-energy state by Stark effects is much smaller than that of a Rydberg state, the energy shift is usually buried under the resolution of the spectroscopic method. The typical resolution of laser-aided spectroscopic detection of energy states is several gigahertz, which is determined by the linewidth of a pulsed tunable laser and the Doppler broadening width of the transition line. Our idea is to use a spectroscopic method having Doppler-free resolution. We employed saturation spectroscopy at the Balmer-α line of atomic hydrogen [2,3]. Since it is possible to construct the system of saturation spectroscopy by using a tunable single-mode diode laser, we can realize an easy-to-use system with an ultrahigh resolution at a low experimental cost.

The experiment has been carried out in an inductively coupled hydrogen plasma. A grounded electrode was inserted into the plasma, and we measured the fine-structure spectrum of the Balmer-α line of atomic hydrogen in the vicinity of the electrode. The light source for saturation spectroscopy was a linearly-polarized, single-mode diode laser. The wavelength of the laser was scanned over the whole range of the Doppler broadened Balmer-α line of atomic hydrogen. A small part of the laser beam was picked up using a beam sampler and was used as the probe beam. The other part of the laser beam was intensified using a diode laser amplifier and was used as the pump beam. The probe and pump beams were injected into the plasma from the counter directions. The probe beam passed through the plasma was introduced into a photodiode detector via an interference filter at the Balmer-α line. The saturation spectrum was obtained from the difference between the absorption spectra in the presence and the absence of the pump beam.

We obtained reasonable agreement between the theoretical Stark spectra and the saturation spectra observed experimentally. The frequencies of the $2p^2P^o_{3/2}$-$3d^2D_{3/2}$ and $2p^2P^o_{3/2}$-$3d^2D_{5/2}$ transitions shifted toward the low- and high-frequency sides, respectively, with the increase in the electric field strength. According to the experimental result, it is considered that the frequency distance between the above two peaks can work as a measure for determining the electric field strength. We determined the electric field strength as a function of the distance from the electrode. The electric field ranged between 15 and 120 V/cm within a distance of 1 mm from the electrode. The minimum change in the frequency distance between the $2p^2P^o_{3/2}$-$3d^2D_{3/2}$ and $2p^2P^o_{3/2}$-$3d^2D_{5/2}$ peaks, which we could identify experimentally, was 10 MHz. This resolution corresponded to 10 V/cm for the detection limit of the electric field. We thus succeeded in the development of a sensitive method for the measurement of the sheath electric field by employing a low-cost, easy-to-use diode laser system.

References

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